Coordinated Autonomy for Persistent Presence in Harbor and Riverine Environments

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LONG-TERM GOALS

In FY 2007 the Naval Postgraduate School (NPS) teamed with Virginia Tech (VT) to conduct fundamental research and experimentation aimed at enabling coordinated autonomous operations by teams of heterogeneous (land, sea, air) vehicles. The primary goal of this research is to develop tools for vehicle-to-vehicle cueing and distributed sensing for shared situational awareness. A long-term goal for this research is persistent area surveillance of harbor and riverine environments by a "distributed autonomous system" (DAS) of networked vehicles and sensors. Under this operational concept, aerial vehicles would function as long-range sensors and provide navigational cues to surface vehicles providing close-up video inspection or interdiction of suspicious vessels. Sensor data analysis and integration would provide automated scene analysis, object detection and tracking, and vision-based autonomous navigation. The system would exploit data from all vehicles and sensors to produce three dimensional maps of the operating environment, buildings, ships, etc.

OBJECTIVES

The main objective of this project was to develop underlying tools and technologies needed to field and demonstrate coordinated operations with a team of autonomous vehicles. To achieve this objective in the 16-month allotted time, the project team focused their efforts on a mutually interesting problem with relevance to current military operations: convoy support by autonomous vehicles. The technologies and capabilities developed by addressing this problem are necessary steps toward achieving our long-term goals in follow-on projects. The problem was decomposed into two near-term project objectives, with an emphasis on experimentation.

UAV-USV cueing

The goal of this project is to develop command and control strategies to support convoy and riverine operations with autonomous vehicles. The concept of operations (Figure 1) involves "tethering" an unmanned aerial vehicle (UAV) to a ground or surface vehicle whose sensor range or maneuverability is constrained by its operating environment. The unmanned ground or surface vehicle (UGV or USV) commands the UAV to survey the area ahead of its intended path. Computer vision techniques will enable the UAV to identify navigational hazards (obstacles) in their path or objects requiring closer

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investigation (targets). The UAV would then provide these situational awareness cues to the UGV or USV so it can take appropriate action.

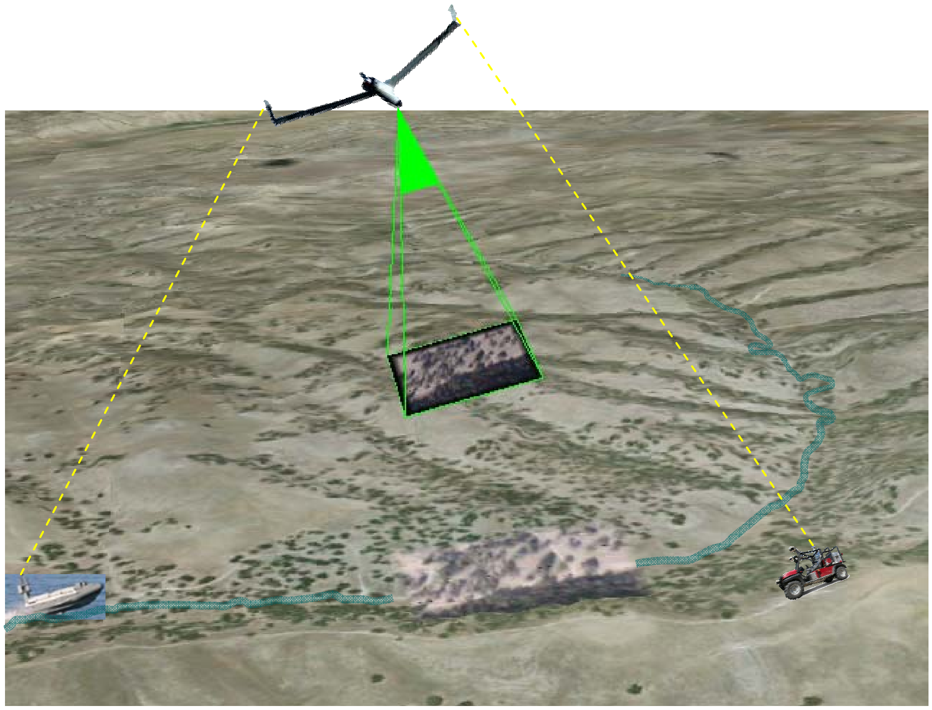

Figure 1: UAV-USV Concept of Operations

Sensor Data Analysis and Integration for Autonomous Vehicles
The goal of this project is to automatically analyze sensor data from unmanned vehicles and provide data visualization for enhanced situational awareness, advanced surveillance capabilities, and improved vehicle autonomy. Vehicle sensors not originally intended for navigation and control still provide sufficient and often superior information than a typical GPS and inertial measurement unit (IMU) can supply. Beyond navigation, these sensors (such as visible-light cameras or LIDAR devices) make a wealth of information accessible that current automated analysis methods can scarcely tap into. This project is aimed at leveraging more of this information through automated analysis and visual integration to make steps towards achieving our long-term goals

APPROACH

As stated above, this project is a research partnership between Virginia Tech and the Naval Postgraduate School. The VT team was led by Principal Investigator Dan Stilwell (USV component), Craig Woolsey (Co-PI and UAV component), and Charles Reinholtz (UGV component). This report will focus on work conducted by the NPS team led by Doug Horner (PI), Isaac Kaminer (UAV component), Mathias Kolsch (Computer Vision), and Sean Kragelund (Project Management, USV component).

UAV-USV Cueing

This project involved several subtasks with varying degrees of coordination with our VT partners:

- Established a common communications architecture. The ITT Mesh Wireless Modem Card was selected as the primary means of vehicle-to-vehicle communications for this project, due to its proven performance and reliability on NPS UAVs used at quarterly Tactical Network Topology (TNT) field experiments.
- Implemented standard inter-vehicle communications protocols. The Joint Architecture for Unmanned Systems (JAUS) was selected based on VT's expertise and their JAUS-compliant UGVs. A common protocol was necessary for VT vehicles to interoperate with NPS vehicles at future system demonstrations. JAUS is a mature, well-documented standard being sponsored and promoted by the Department of Defense (DoD)
- Selected Wolfgang Baer's Perspective View Nascent Technology (PVNT) to perform target detection and localization from UAV video. PVNT consists of a user-operated interface and a digital terrain database. It receives UAV telemetry and video in real-time, and generates a synthetic view of the terrain for comparison with the actual video. When a human operator clicks a point in the synthetic view, the location is relayed to the UAV. In this way, targets can be localized to within the accuracy of the digital terrain data, which is typically better than accuracies achieved by low-cost UAV inertial sensors.
- Established a development and experimentation program that built upon our most mature vehicle platforms and capitalized on existing UAV test schedules during NPS TNT exercises. Our system baseline consisted of the VT Rocky UGV, the NPS Rascal UAV, and Wolfgang Baer's Persistent View Nascent Technology (PVNT) software.
- Perform land-based testing of new capabilities before transitioning them to maritime platforms.

Sensor Data Analysis and Integration for Autonomous Vehicles

The operational and technical requirements for developing this technology are:

- access to data, both live and stored for offline processing (repeatability), both vehicle telemetry and video, including time stamps;
- data analysis capabilities, mainly a set of image/video processing and computer vision methods reflecting recent advances;
- powerful graphics capabilities, both regarding the rendering hardware and high-performance, cutting-edge software packages;

Time-synchronized video and sufficient sensor telemetry was not available and getting this data from vehicles in real-time requires knowledge of their communication protocols. Therefore, we addressed the first requirement by building a protocol and data management suite for autonomous vehicles called AVSuite. It facilitates communication among autonomous vehicles, their operators, and data analysis stations. It also permits data storage and replay through various interfaces. Our approach provides for protocol extensibility to accommodate future needs and changes.

We addressed the second and third requirements with a new application developed for this project called VideoTexture. This sensor data analysis and integration tool can operate on either real-time or stored mission data. It facilitates a number of functions ranging from video stabilization and mosaicing to user interaction with large three-dimensional spatial models. Our development approach for Video Texture used the following:

- Real-time data analysis methods, robust model estimators, and methods designed to deal with real-world problems such as video transmission noise;
- OpenCV for basic computer vision functionality as well as portability;
- Advanced OpenGL features for good rendering performance;
- OpenSceneGraph as a high-performance, up-to-date graphics package that allowed for full customization and paged levels of detail which are required for rendering large areas of virtual terrain. Furthermore, OpenSceneGraph is based on OpenGL, improving portability.
- We focused on (UAVs) to capture data that was visually challenging, yet technically feasible.

WORK COMPLETED

Sensor Data Analysis and Integration for Autonomous Vehicles

AVSuite is an extensible and portable (cross-platform, Windows, Linux) library for autonomous vehicle data management, including communication, protocol conversion, and data storage. This allows multiple autonomous vehicles, control stations, and data logging stations using different protocols to communicate. Adding additional inbound and outbound protocols to the library is straightforward. AVSuite can store time-stamped data, including video, and replay data logs at varying speeds. Temporal synchronization between telemetry data streams and video is built-in.
Protocols and data formats currently supported by AVSuite include: Cursor on Target (CoT), JAUS, Predator Exploitation Support Data (ESD), PVNT, and various NPS protocols developed to support UAV experimentation. For this project, rather than forcing NPS researchers to modify their protocols, we used AVSuite to translate incoming/outgoing JAUS messages to/from their expected formats.

VideoTexture is a sensor data analysis and integration tool. It takes real-time or logged mission data and video as inputs and performs automated analysis and data visualization. It uses "telemetry" data, which for our purposes includes aircraft pose, i.e. position and orientation, camera position, direction and zoom setting. After data analysis, it displays the vehicle, its flight path and user annotations in combination with the virtual terrain. The video data is persistently integrated with the virtual terrain in real-time. Its ability to project 2D video onto virtual 3D terrain in real time creates a permanent mosaic, enhancing spatial awareness and providing a means of updating the terrain imagery database.
VideoTexture's main features are:

- 3D UAV, video, and topography visualization
- 6DOF motion and perspective projection model for perspective views (trapezoidal geo-rectification)
- improved geo-registration of projected video through frame-by-frame mosaicing
- telemetry data correction
- relative UAV/camera pose calculation solely based on video (no reliance on telemetry data)
- digital video stabilization
- various video de-interlacing modes
- robust to moving and changing video scenes and video noise (drop-frame decision)
- satellite image (terrain) can be permanently updated based on UAV sensor data
- graphical user interface for map annotations, object tracking selection, and road overlays.
- symbols conforming with MIL-STD-2525B
- all features are available at real-time processing speeds
- platform portability

VideoTexture's mosaicing and geo-registration capabilities lay the groundwork for object tracking through visual means, further aided through a physical motion model. We will also improve geo-registration of projected video through frame-to-satellite image mosaicing. VideoTexture's annotation capabilities allow users to mark on the terrain the 3D positions of features, paths, and regions which can be designated to represent items like: target location, target search region, no-fly zones, and ingress and egress routes. Users can view mission video in real-time or playback a previous mission together with a video mosaic painted onto the terrain 1) as the mission progresses, or 2) a fraction of the entire video. VideoTexture allows interactive examination, annotation, and recording of analysis results for later display or for immediate use in operational mission planning.

RESULTS

UAV-USV Cueing

The work for this portion was completed in stages coinciding with the quarterly TNT field experiment schedule. In August 2006, a Virginia Tech team traveled to Camp Roberts, CA for our first joint experiment. The goal of this experiment was to test Mesh point-to-point communications between the NPS Rascal UAV and a surrogate UGV. NPS researchers had developed a Rascal interface whereby network operators could command the UAV waypoint, orbit and camera parameters using a simple binary protocol. VT researchers implemented this protocol with their UGV control software. Using a pickup truck, a laptop, and the inertial navigation system (INS) from their ground vehicle, we performed a simulated UAV-UGV operation. The laptop took control of the UAV and proceeded down a narrow roadway with limited visibility of its forward path. The UAV successfully tracked the ground vehicle and an artificial obstacle was visible in the UAV video before it could be seen on the surrogate UGV video (Figure 2). This validated our concept of operations.

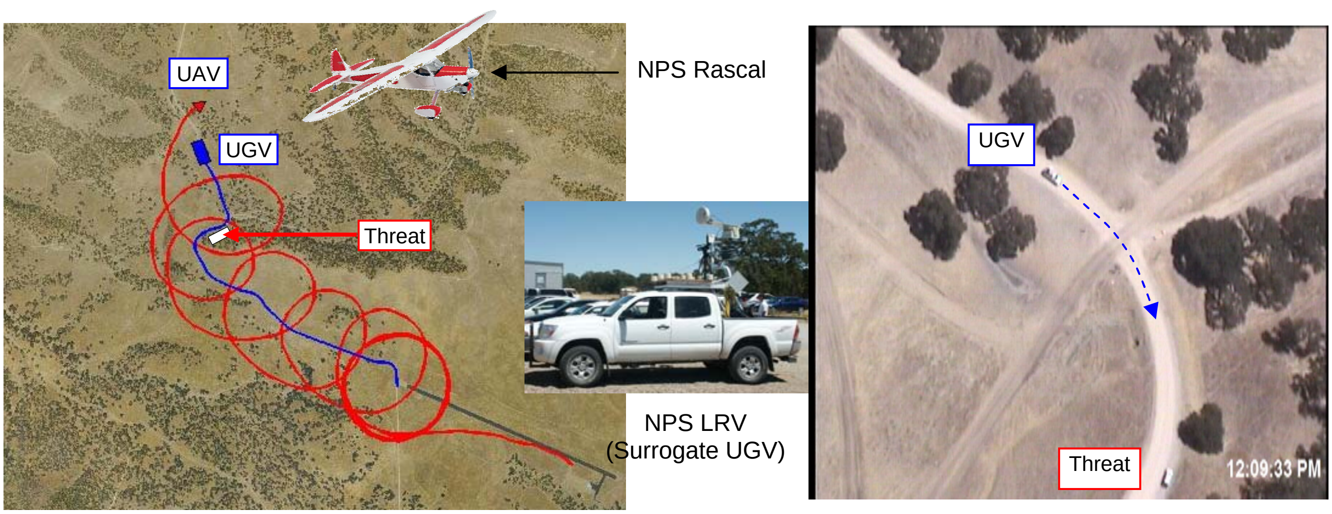

Figure 2: Initial UAV-UGV cueing (surrogate UGV) experimental data and aerial video still

In November 2006, the VT team shipped the VT UGV ("Rocky") to Camp Roberts to perform a follow-up experiment with the actual unmanned vehicles and UAV targeting software planned for our final demonstration. In this experiment, the UGV tasked the UAV to continuously monitor a point on the Rocky's preplanned path. As Rocky navigated a series of predefined waypoints, Rascal provided situational awareness and forward surveillance of Rocky's intended path. Aerial video was transmitted to the UAV ground station, where an operator using GIS-based Perspective View Nascent Technology

(PVNT) software identified and localized an obstacle along the planned UGV route. The obstacle's location was automatically relayed to Rocky, which autonomously modified its mission to circumnavigate the point and perform up-close video inspection of the object with a side-mounted camera (Figure 3). These capabilities were transitioned to the SeaFox USV and field-tested on a reservoir at Fort Hunter Liggett, CA. in April and May prior to our primary system demonstration at Tyndall AFB, FL during AUV Fest 2007.

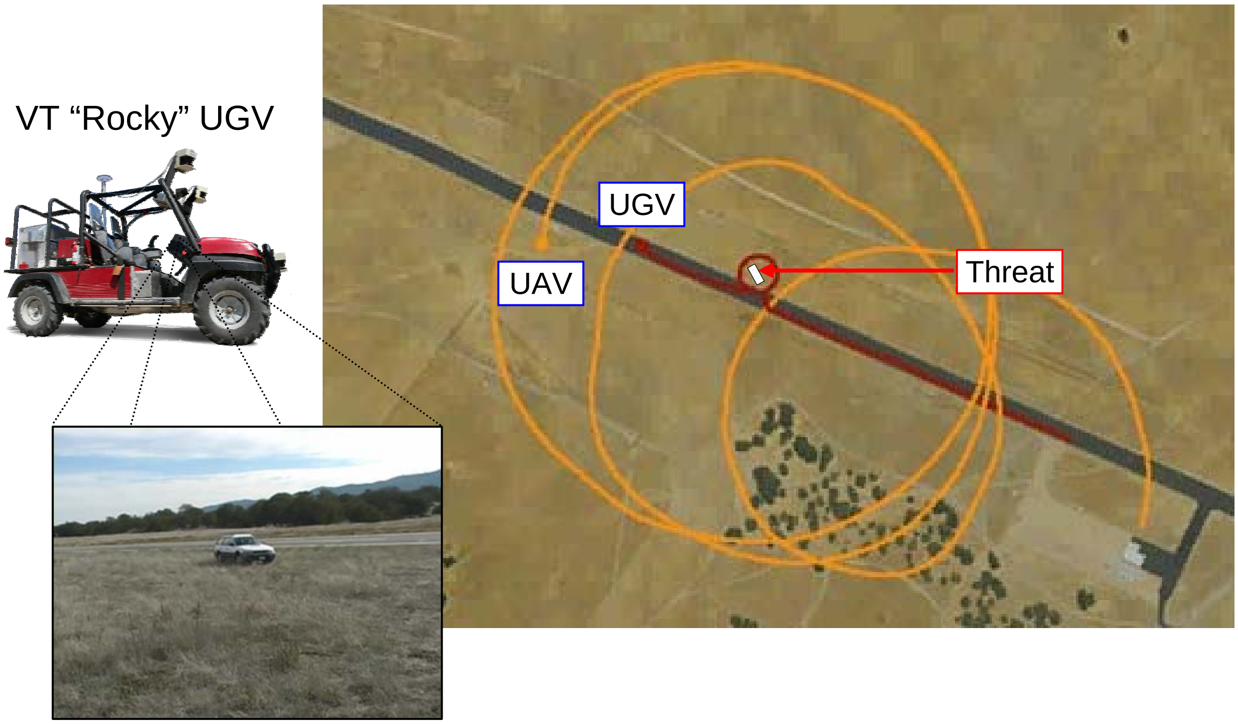

Figure 3: Follow-up UAV-UGV cueing experiment; this marked the first time that the NPS Rascal UAV was controlled by another autonomous vehicle

During AUV Fest 2007, we demonstrated UAV-USV cueing between Rascal and SeaFox in a riverine environment. Figure 4 shows the vehicle positions as Rascal operated under SeaFox control. A forward observer with a laptop and ITT Mesh card running PVNT software detected and localized an artificial target (Figure 5). This data was relayed to SeaFox via the Rascal UAV. At this time, however, SeaFox was not capable of autonomously circumnavigating a target. Instead, it treated inspection locations received from the UAV as waypoints to be followed. In July 2007, we implemented new navigation algorithms based on artificial potential field theory to provide a more robust target inspection capability. This capability was demonstrated in August 2007 experiments on Monterey Bay and Lake San Antonio, CA. in (Figure 6). The plot on the left shows SeaFox executing a pre-programmed box pattern when a network user sends SeaFox a target location. SeaFox transits to the target location, orbits the target for a prescribed time, then returns to the loiter box. The plot on the right shows SeaFox orbiting a moving target after a network user provides a target position, speed, and heading.

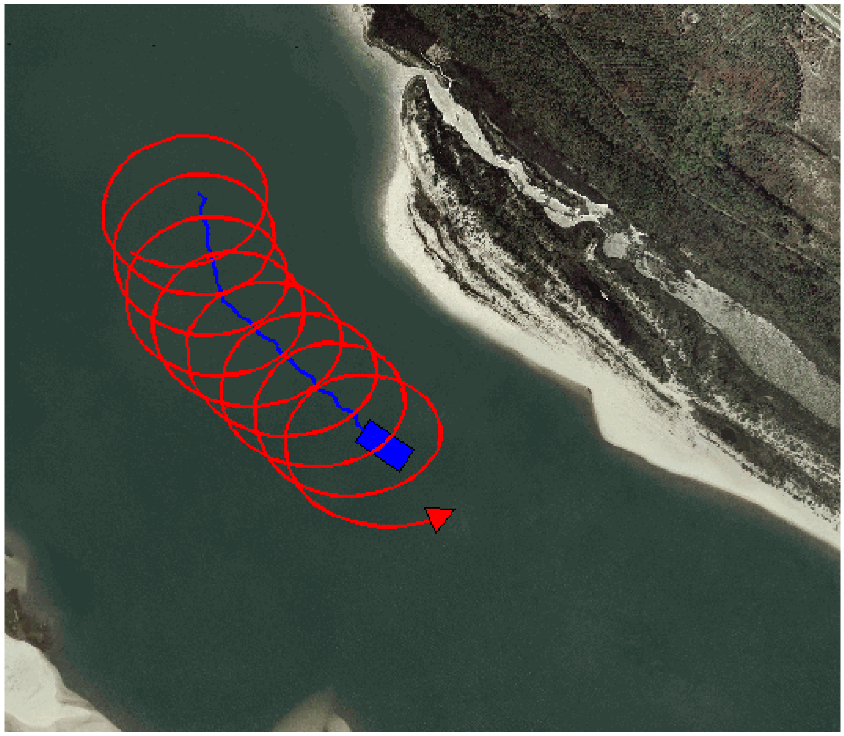

Figure 4: UAV-USV cueing between Rascal and SeaFox at AUV Fest 2007

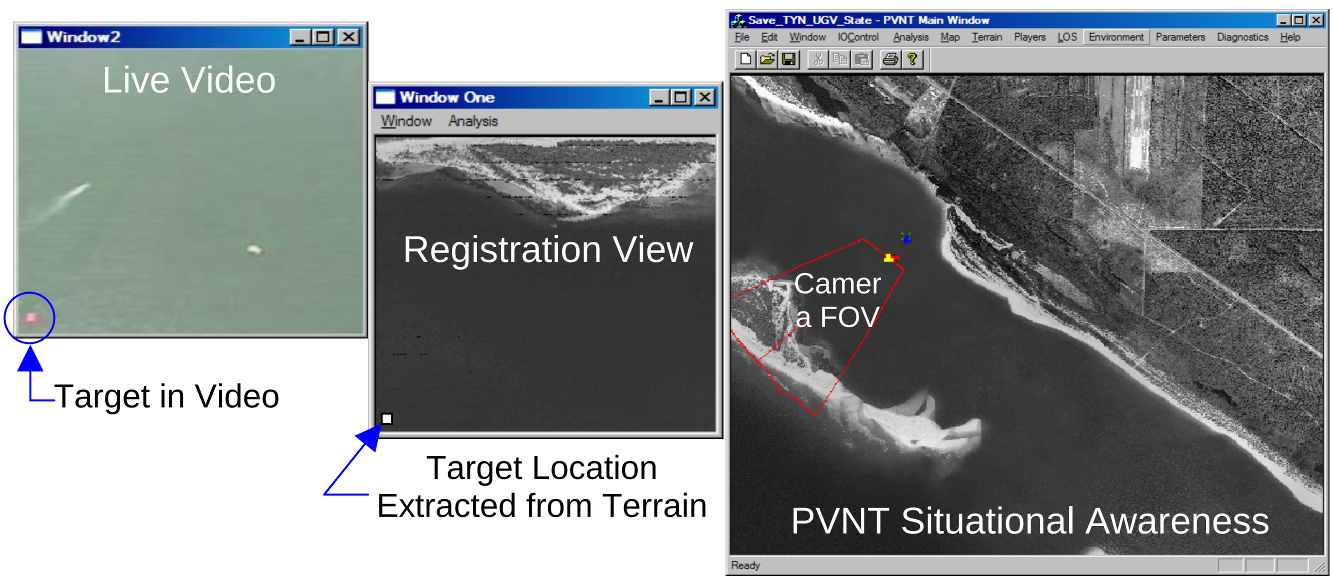

Figure 5: Screen shots of PVNT image mensuration software used for target detection and localization from NPS Rascal video at AUV Fest 2007

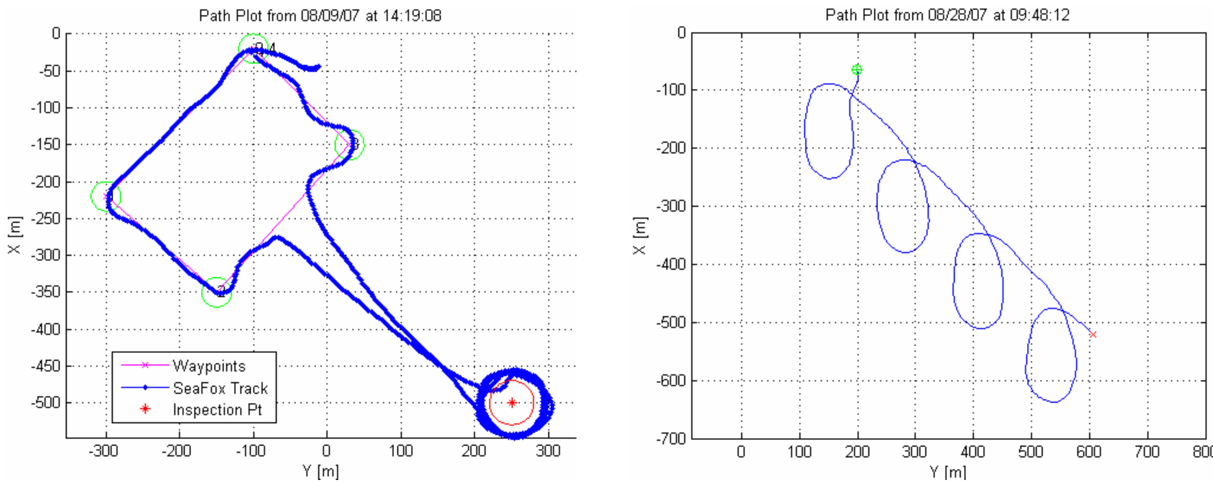

Figure 6: SeaFox telemetry plots that depict new target inspection behaviors. At left: SeaFox departs from a predefined loiter box to orbit a target position received over the network. At right: SeaFox orbiting a moving target when cued with target position, range, and bearing

Sensor Data Analysis and Integration for Autonomous Vehicles
AVSuite and VideoTexture were field-tested at several exercises, including TNT and AUV Fest 2007. Both components were deployed in the live data environment and captured data for later offline use. A typical scenario is shown in (Figure 7).

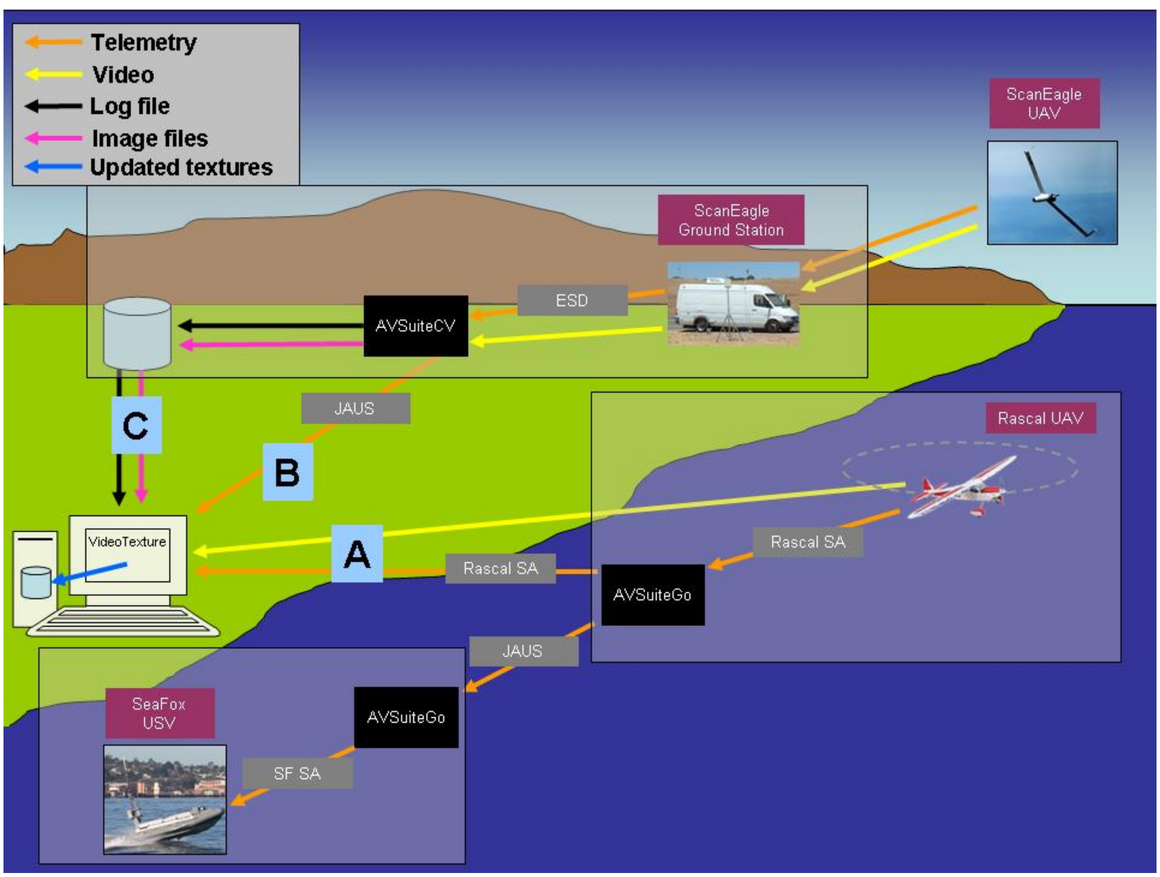

Figure 7: A sample scenario employing AVSuite and VideoTexture

The UAV-USV cueing experiments conducted at TNT field experiments showcased the versatility and usefulness of the AVSuite application. AVSuite was successfully installed on both the SeaFox USV (Redhat Linux 8.0) and the Rascal UAV (Windows XP). Each vehicle ran two instances of the program to translate inter-vehicle messages to/from standardized JAUS messages (Figure 8). These experiments were crucial to demonstrating UAV-USV cueing within the JAUS communications framework chosen for this project. As a result, the NPS vehicles achieved JAUS Level One Interoperability, and were able to communicate with Virginia Tech's vehicles at AUV Fest 2007.

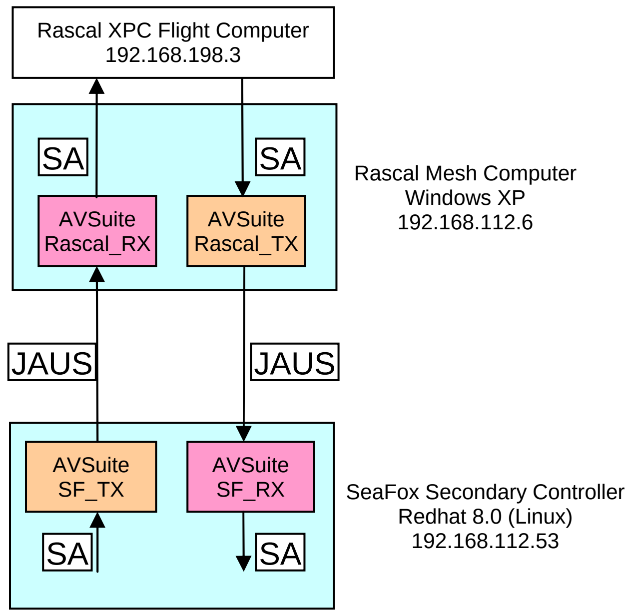

Figure 8: AVSuite used as a Protocol Translator for the Rascal-SeaFox cueing demonstration

All VideoTexture features described above were successfully tested. Figure 9 shows 3D Camp Roberts terrain with the video projected onto it. Figure 10 shows more detailed snapshots of terrain with elevation and the (brown-grey) video overlaid. Figure 11 demonstrates the real-time video mosaicing capability which corrects the telemetry data based on video sensor measurements (feature-based tracking and self-localization).

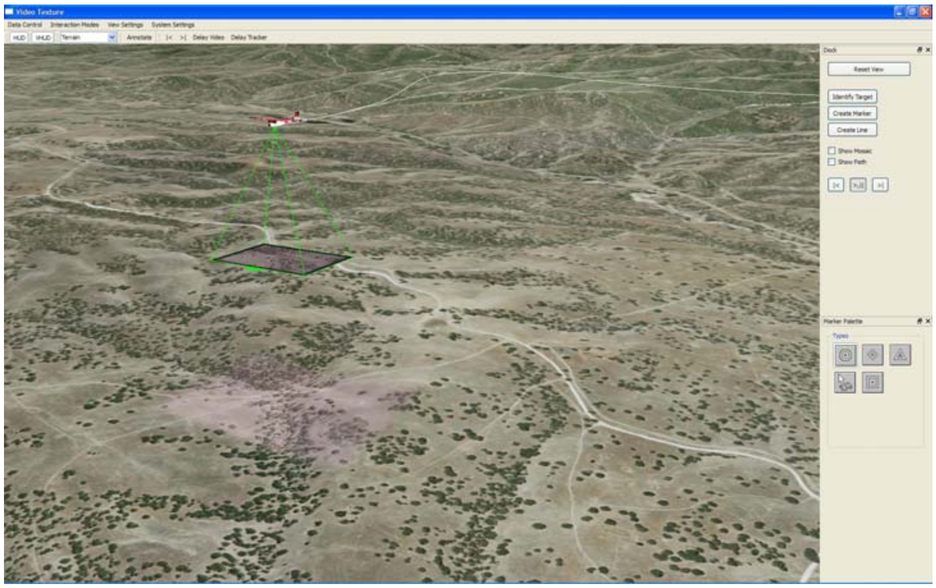

Figure 9: Camp Roberts and UAV video. The UAV "projects" its video onto the 3D terrain.

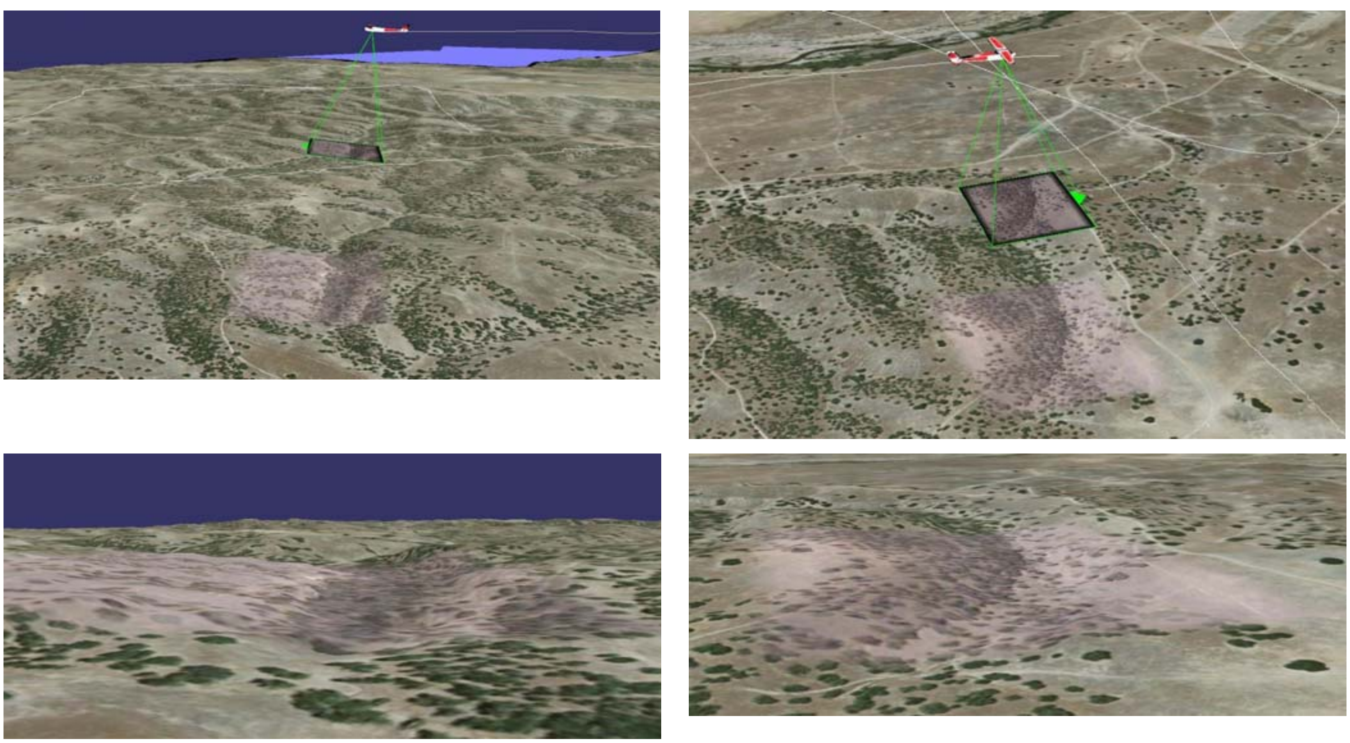

Figure 10: Two UAV positions (on the left and right) and two view angles of the respective video onto the terrain (top and bottom).

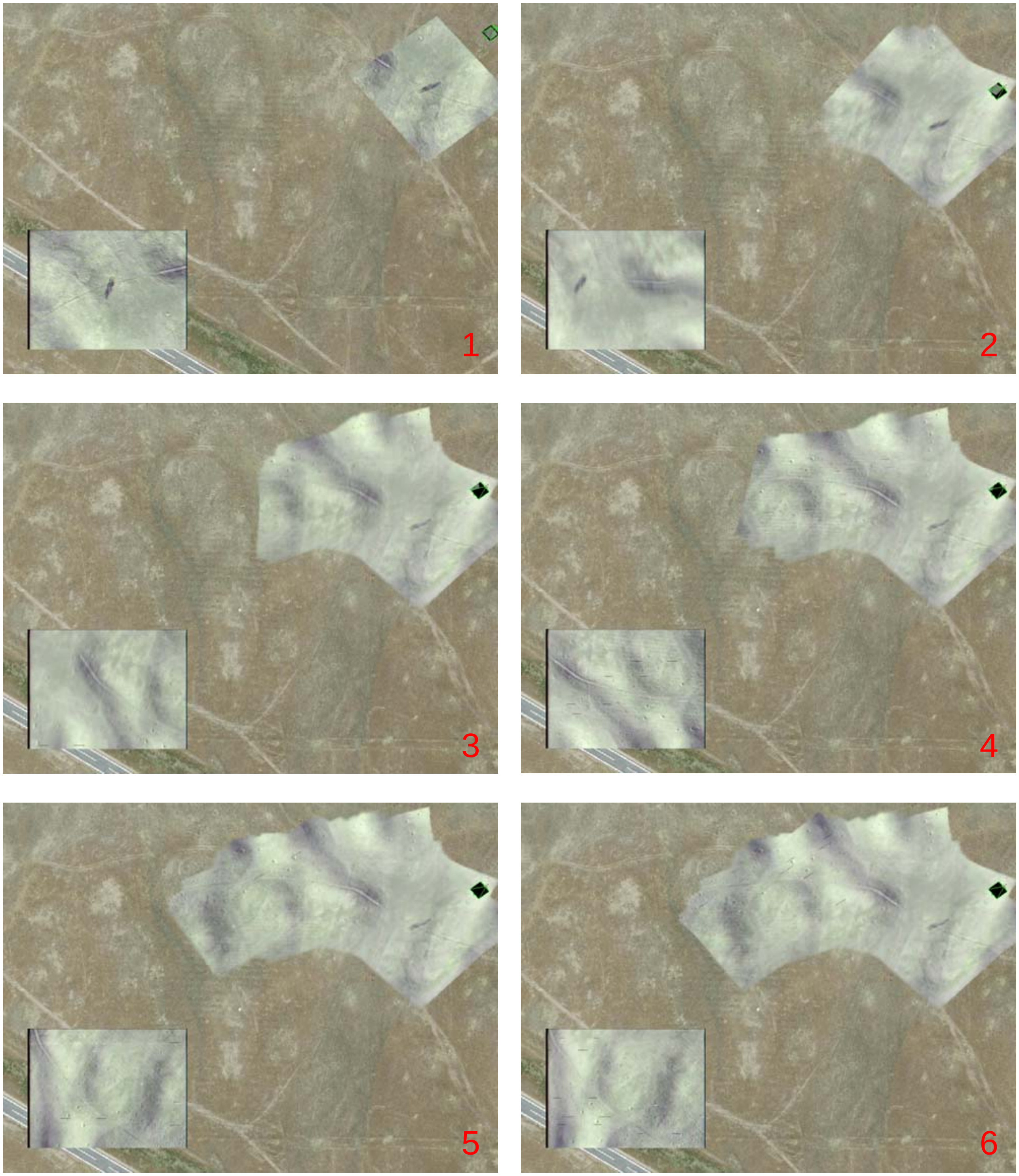

Figure 11: Sequence of images showing how a video mosaic is painted onto terrain data.

Figure 12 shows some of the annotation capabilities of the VideoTexture application. The user has marked a road with "geo-stationary" markers. The right image shows the same information in a more familiar 2D view, also using MIL-STD-2525B icons.

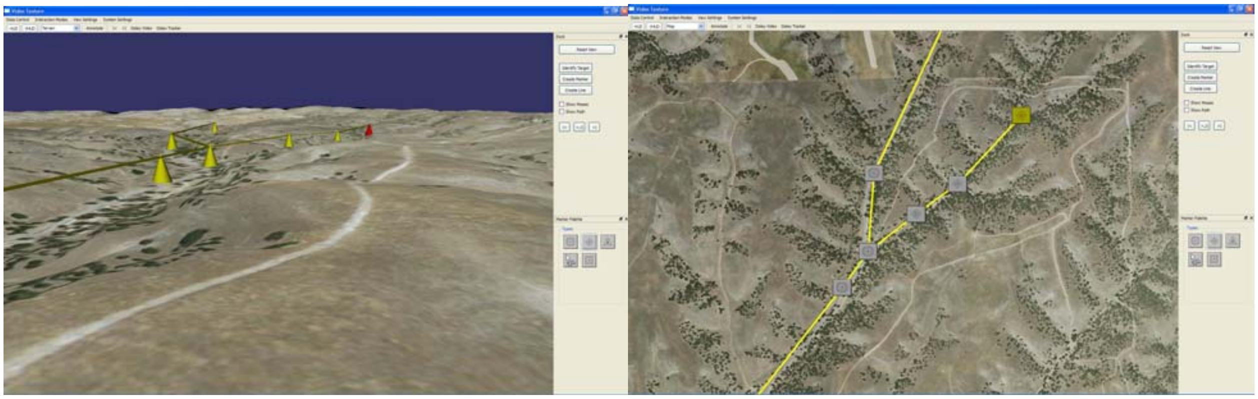

Figure 12: Terrain annotation with the VideoTexture application, 3D view on the left and 2D map view on the right.

RELATED PROJECTS

The work of our Virginia Tech research partners is discussed in a project entitled "Coordinated Sensing and Control for Surveillance and Tracking by Heterogeneous Autonomous Vehicle Teams."

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HONORS

M. Kolsch
Invited presentation at the 2007 Homeland Security - Research*Innovation*Transition Conference.
Invited participant: DARPA ISAT Summer Study on “Integrating Virtual and Real.”